# DARK ENERGY SPECTROSCOPIC INSTRUMENT

cosmology results from the Data Release 1

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In the territory of the
TOHONO O'ODHAM
Dr. Jacelle Ramon-Sauberan (2021)

# DARK ENERGY SPECTROSCOPIC INSTRUMENT

- Kitt Peak National Observatory
- Nicholas Mayall telescope
- 40M spectra

# SCIENTIFIC GOALS

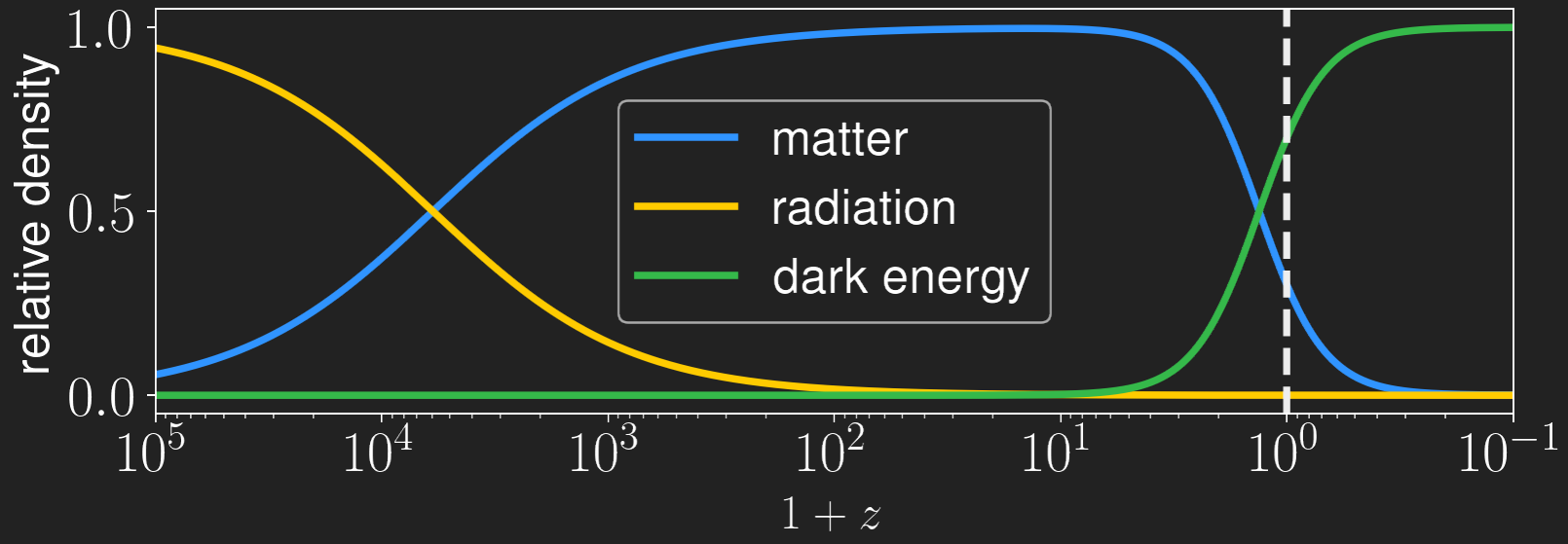
# DARK ENERGY IS OUR MAIN TARGET

Characterize the expansion history in the *Dark Energy* era

Baryon acoustic oscillations

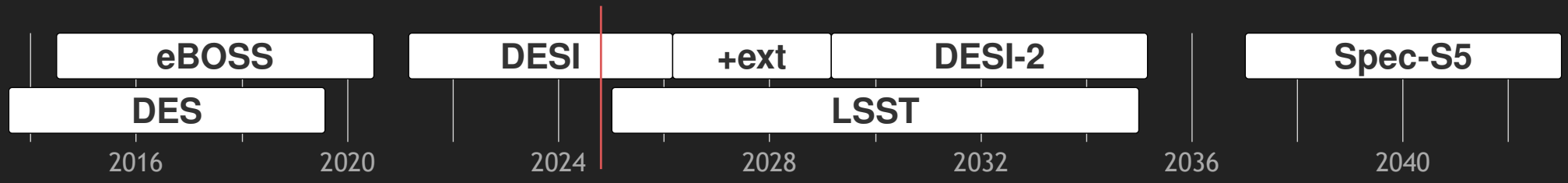
Characterize growth of large scale structure

Redshift-space distortions

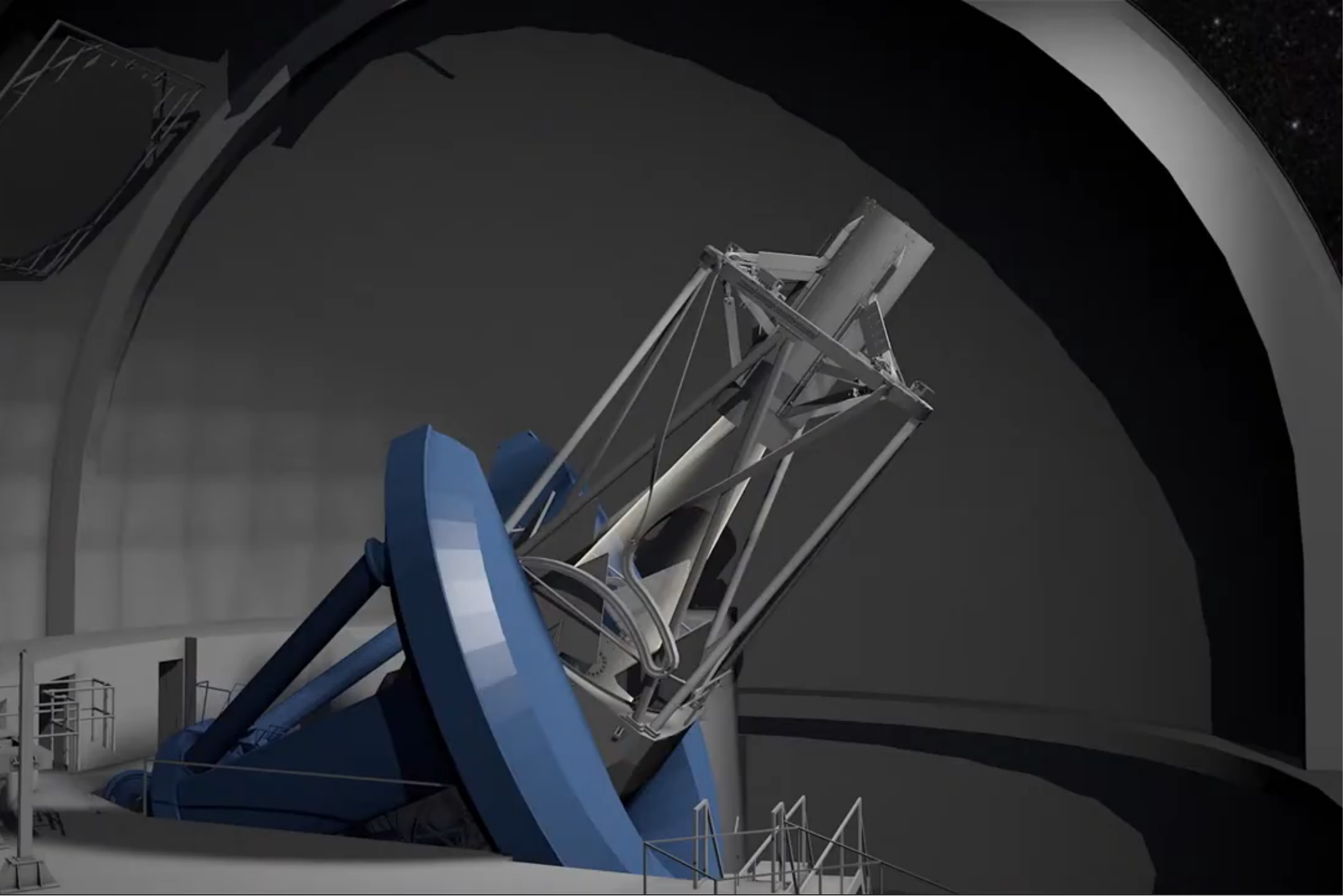


# DARK ENERGY TASK FORCE (2006, 2012)

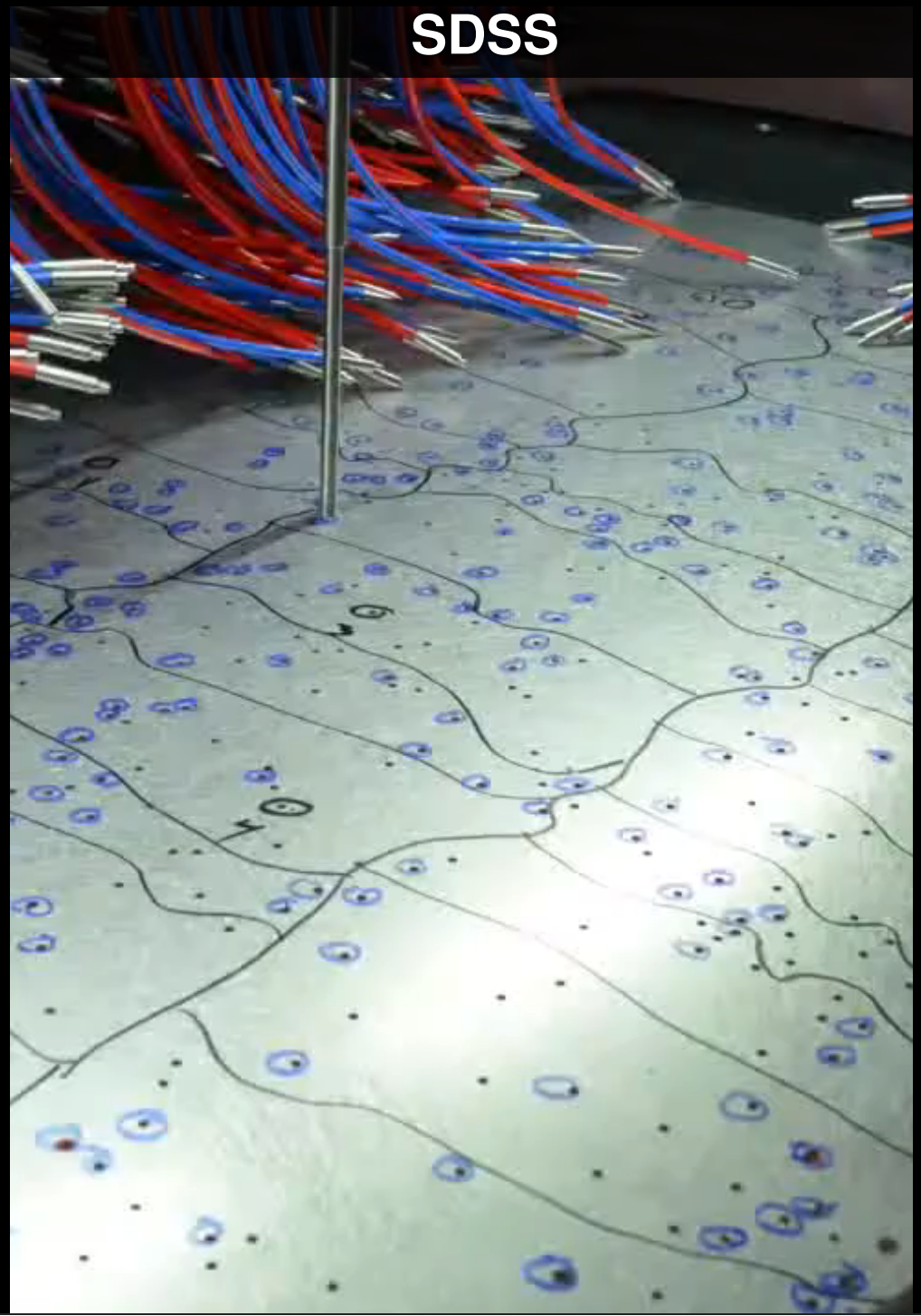
- Stages I & II: Discovery phase & 2000s
- Stage III: BOSS, DES, +
- **Stage IV: DESI, LSST, +**



# THE INSTRUMENT

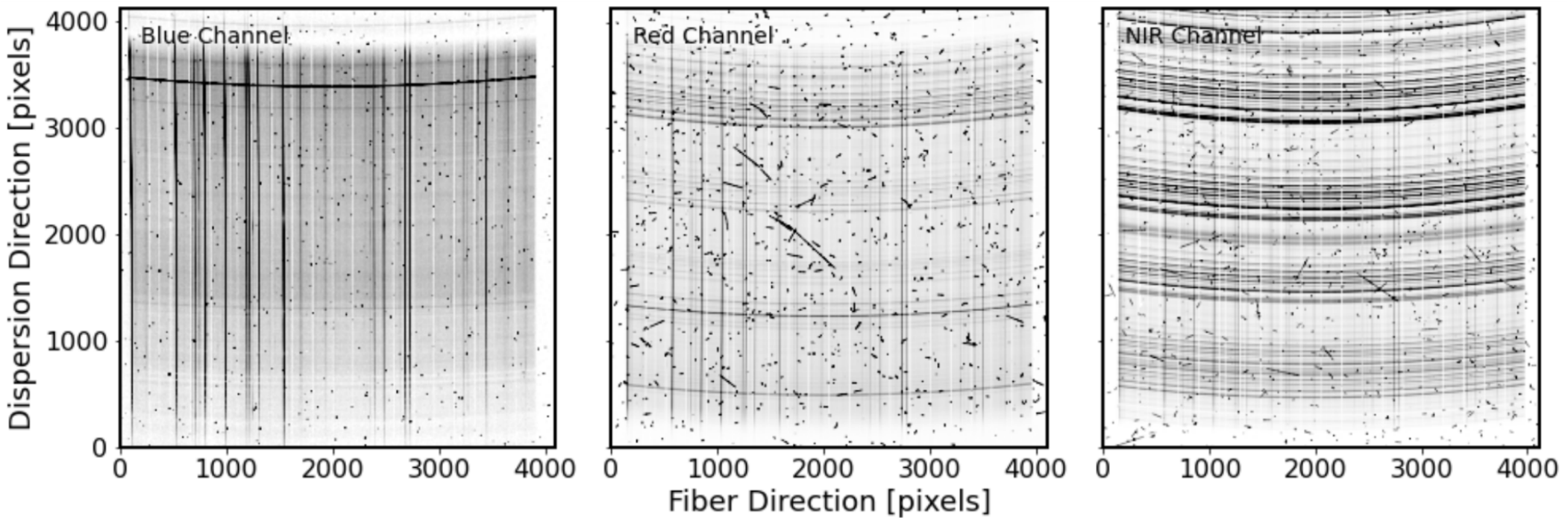


SDSS

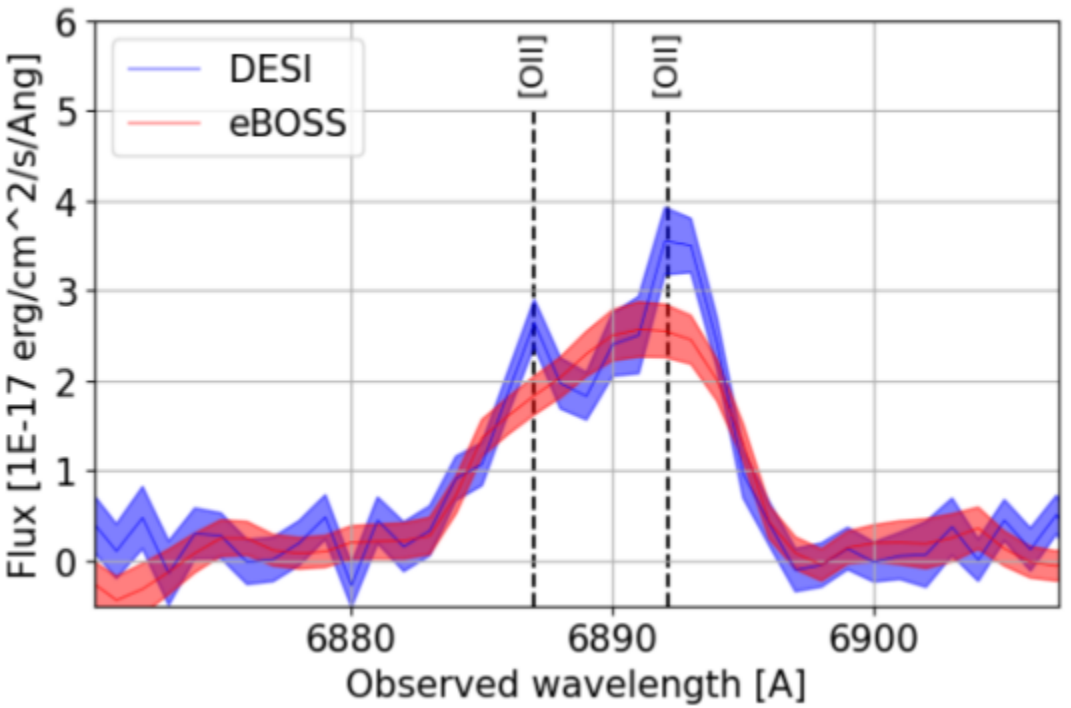


DESI

# 5000 SPECTRA IN 30 MINUTES



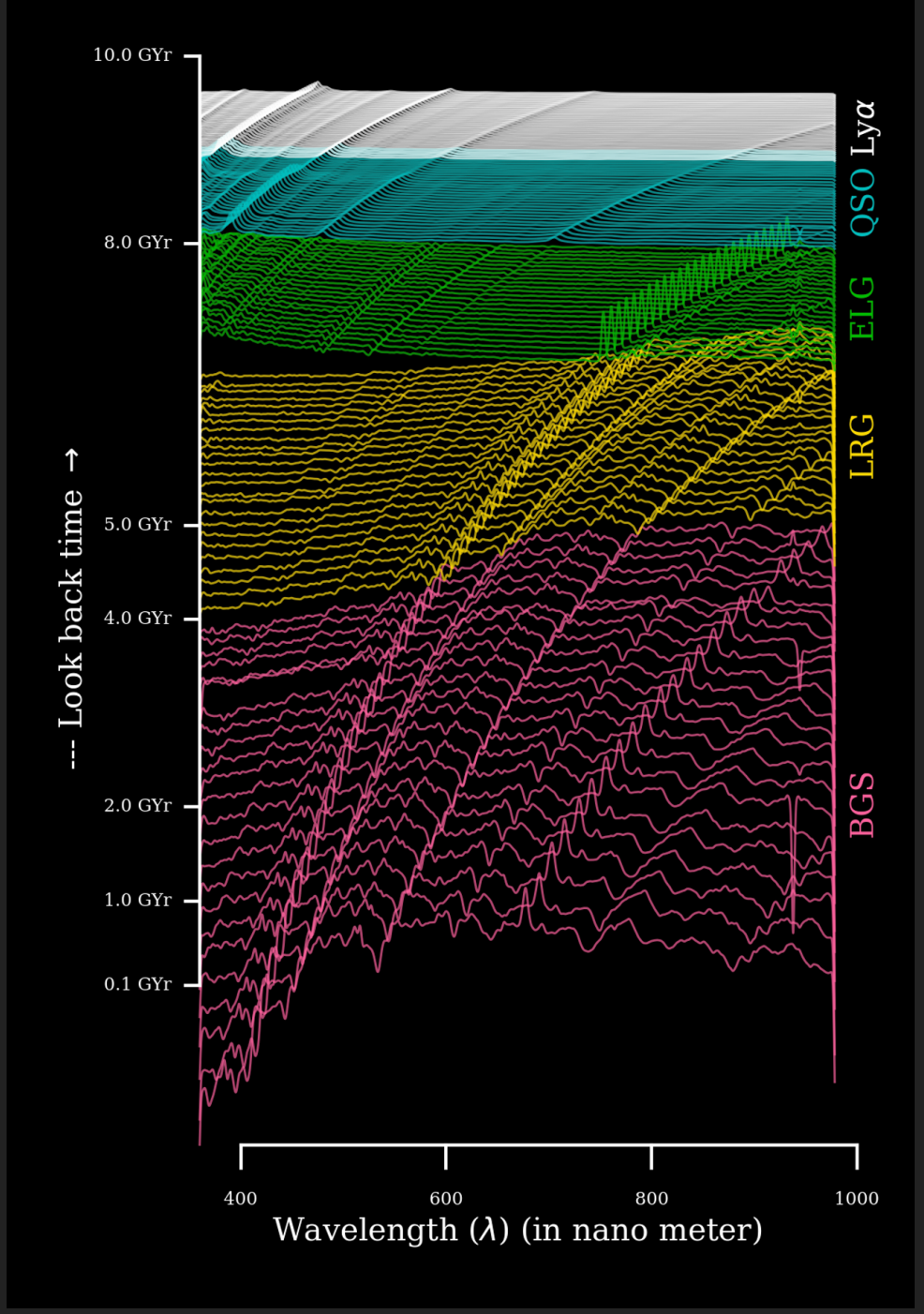
# AT HIGH RESOLUTION




Exposure times:

- **DESI:** 15 minutes
- **eBOSS:** 1 hour

Resulting in a 3D map of galaxies and quasars in the redshift range
$0.1 < z < 4.16$



Bright Galaxy Sample (BGS) $0.1 < z < 0.4$

Luminous Red Galaxies (LRG) $0.4 < z < 1.1$

Emission Line Galaxies (ELG) $0.8 < z < 1.6$

Quasars (QSO) $0.8 < z < 2.1$

Lyman-alpha forest (Ly-α) $1.77 < z < 4.16$

# LEGACY SURVEYS



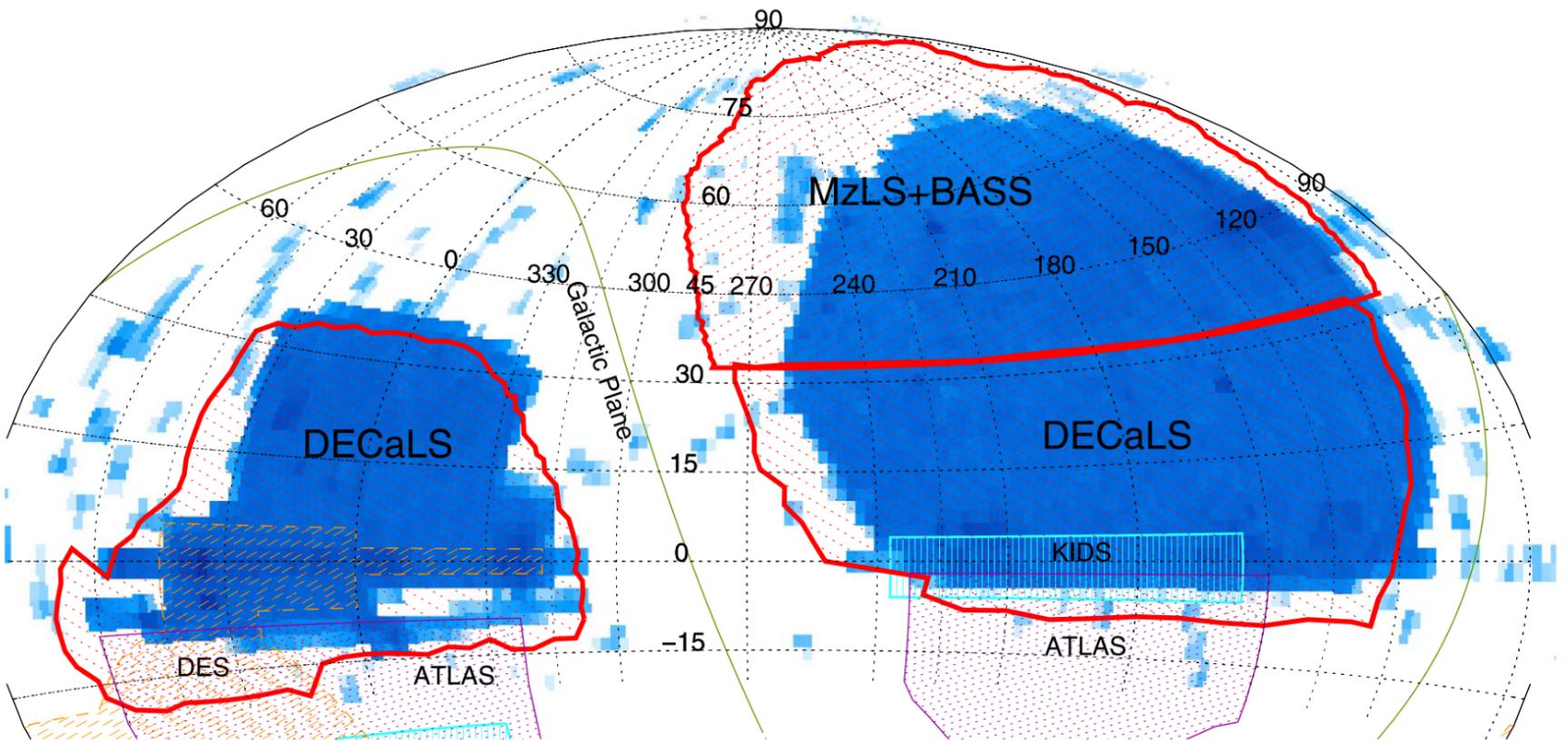



**Figure 1.** Footprints of the optical imaging surveys contributing to DESI imaging, demarcated by the thick red outlines, are shown here in an equal-area Aitoff projection in equatorial coordinates. The region covered by the BASS and MzLS surveys is almost entirely in the North Galactic Cap (NGC) at declinations $\delta \geqslant +32°$, and DECaLS covers the entire South Galactic Cap and the $\delta \leqslant +34$ regions in the NGC. The regions covered by existing wide-area spectroscopic redshift surveys (SDSS, 2dF, and BOSS; Colless et al. 2001; Abazajian et al. 2009; Abolfathi et al. 2018) are shown in the blue gray scale in the map provided, where the darker colors represent a higher density of spectroscopic redshifts. The Legacy Surveys provide deeper imaging and can leverage the existing spectroscopy in these regions, unlike most other existing or ongoing deep imaging surveys (e.g., DES, ATLAS, KIDS, etc.; The Dark Energy Survey Collaboration 2005; de Jong et al. 2015; Shanks et al. 2015).

# OBSERVATIONS >70% COMPLETED

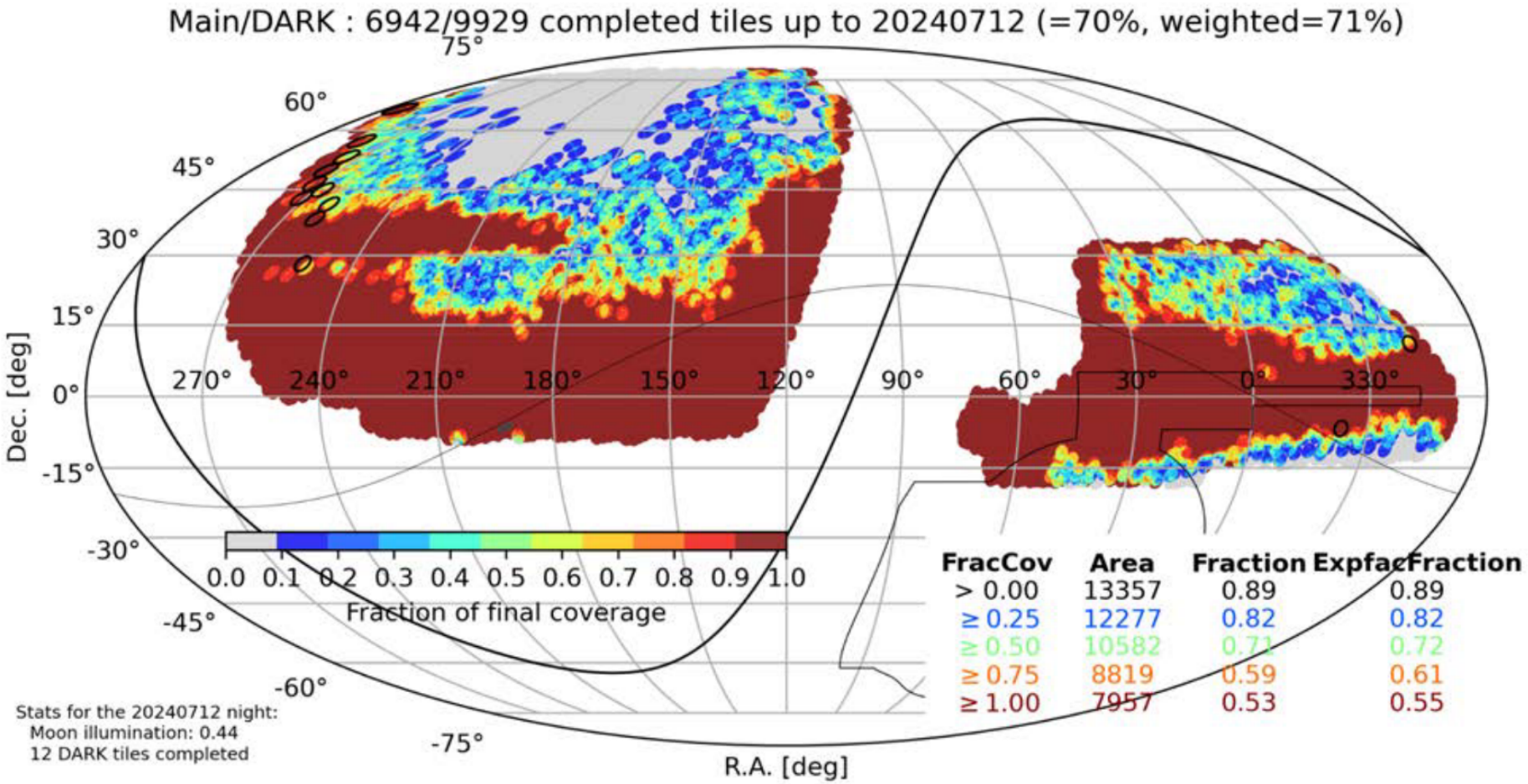
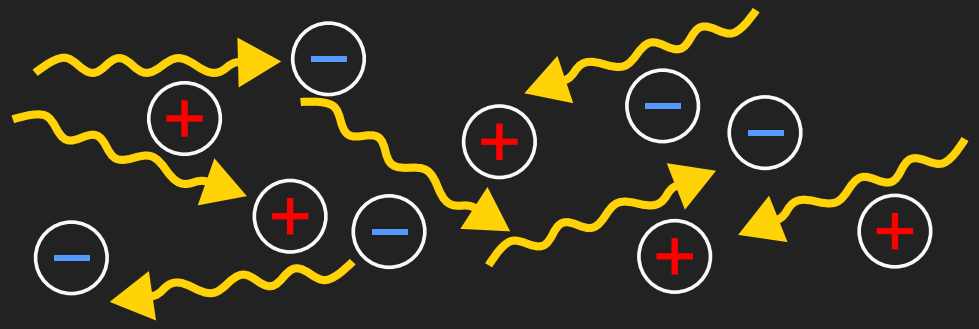



*Figure 5. Fraction completed for the dark-time program, with red indicating areas that have achieved full coverage.*

# BARYON ACOUSTIC OSCILLATIONS

# PHYSICAL MECHANISM

- From Big Bang to $z \approx 1100$, baryons and photons are strongly coupled.

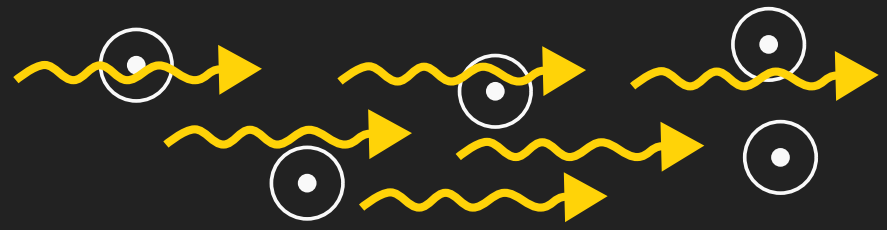


- Acoustic waves propagate at:

$$c_{\mathrm{s}}(z) = \frac{c}{\sqrt{3\left(1 + \frac{3}{4}\frac{\rho_{\mathrm{B}}(z)}{\rho_{\gamma}(z)}\right)}}$$

# PHYSICAL MECHANISM

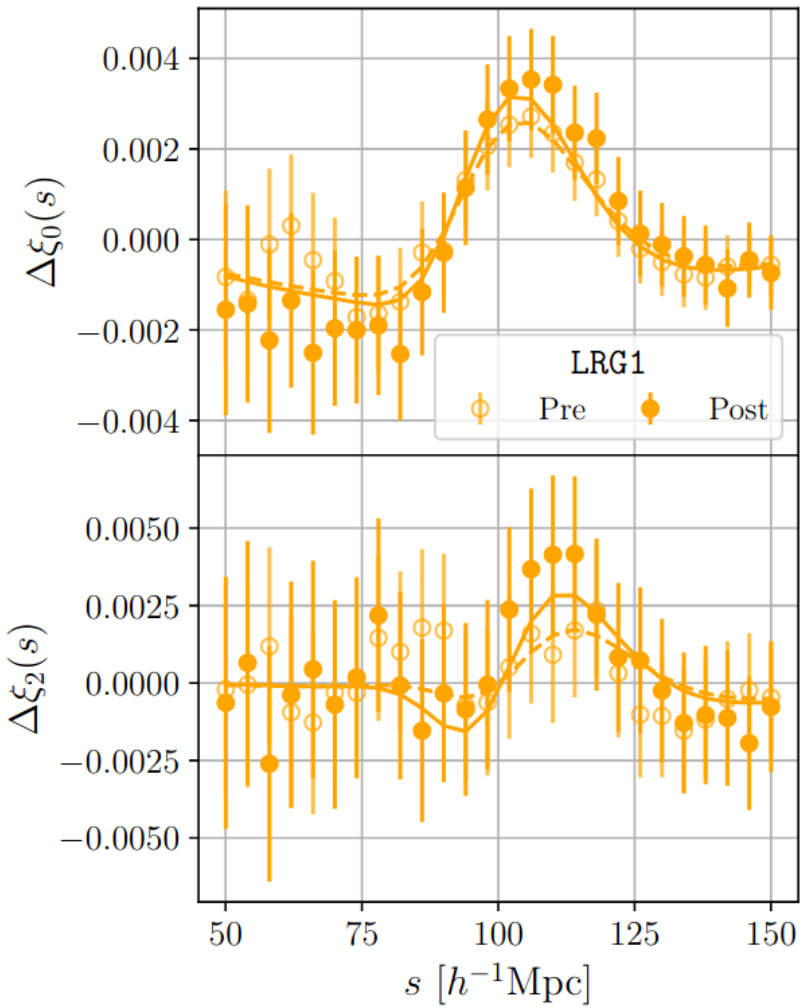
- At $z \approx 1100$, temperature is low enough to form HI. Acoustic oscillations stop.

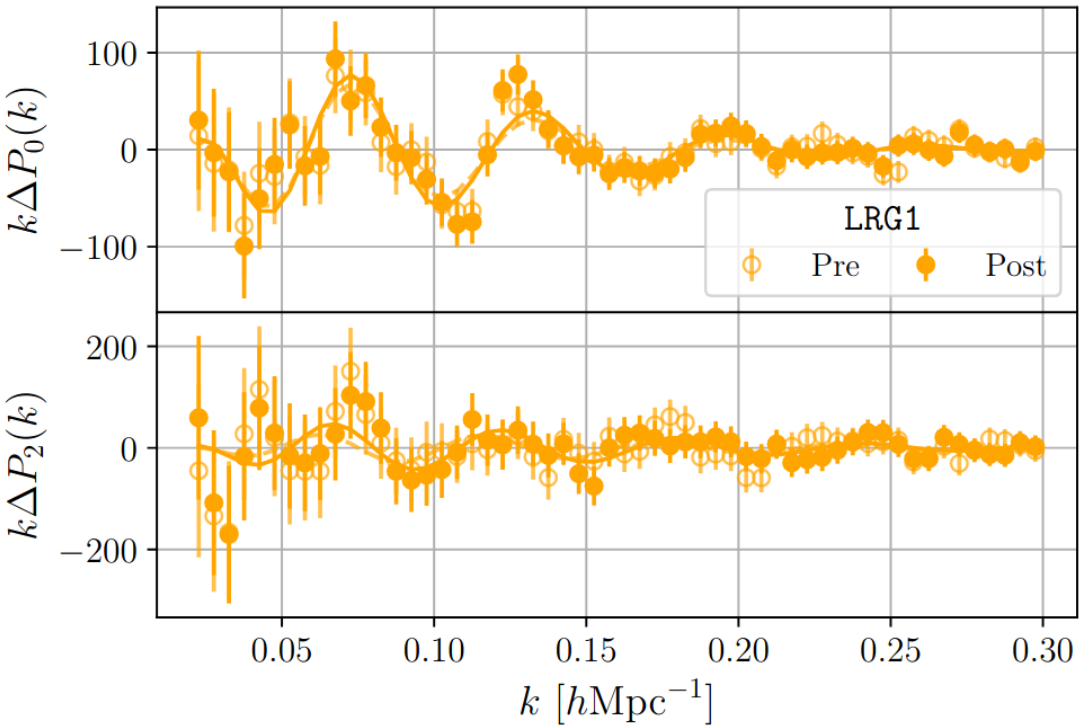


- Acoustic modes can be observed in the distribution of matter (and photons). Fundamental mode is given by:

$$r_{\mathrm{d}} = \int_{z_{\mathrm{d}}}^{\infty} \frac{c_{\mathrm{s}}(z)}{H(z)} dz$$

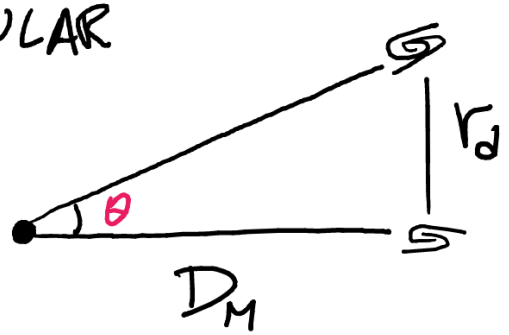
# BAO IN THE GALAXY DISTRIBUTION



# BAO AS A STANDARD RULER

ANGULAR




$$\frac{1}{\theta} = \frac{D_M(z)}{r_d} = \frac{c}{r_d}\int_0^z \frac{dz}{H(z)}, \quad H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \dots}$$

RADIAL


$$\frac{c\Delta z}{H(z)} = r_d \Rightarrow \frac{1}{\Delta z} = \frac{c}{H(z)r_d} \equiv \frac{D_H(z)}{r_d}$$

ANOTHER BASIS:

- ISOTROPIC ⊙ $\frac{D_V}{r_d} = \left[z\left(\frac{D_M}{r_d}\right)^2\left(\frac{D_H}{r_d}\right)\right]^{1/3}$
- ANISOTROPIC ⊕ $\frac{D_M}{D_H}$

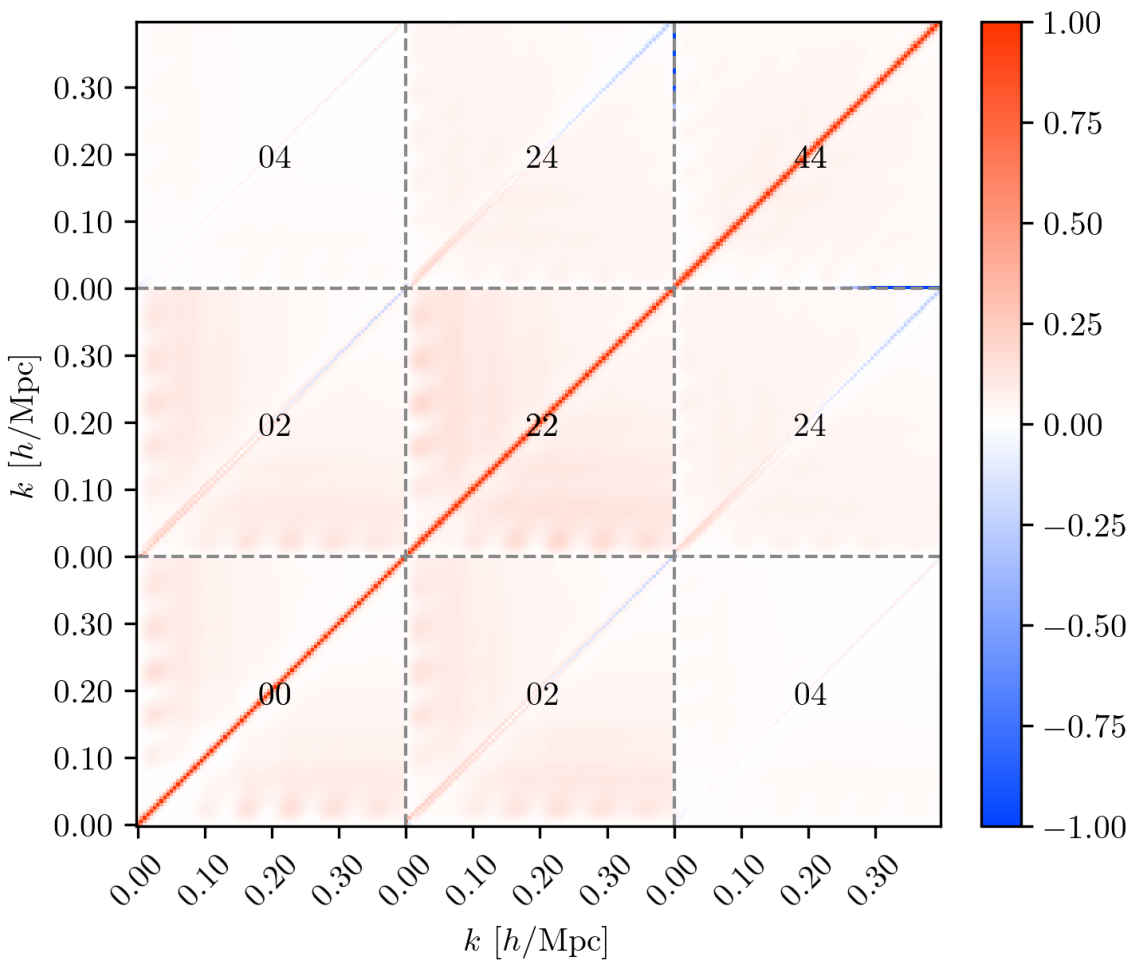
# THE BAO MEASUREMENTS

| tracer | redshift | $N_{\rm tracer}$ | $z_{\rm eff}$ | $D_{\rm M}/r_{\rm d}$ | $D_{\rm H}/r_{\rm d}$ | $r$ or $D_{\rm V}/r_{\rm d}$ | $V_{\rm eff}$ ($\rm Gpc^3$) |
|---|---|---|---|---|---|---|---|
| BGS | $0.1-0.4$ | 300,017 | 0.30 | — | — | $7.93 \pm 0.15$ | 1.7 |
| LRG | $0.4-0.6$ | 506,905 | 0.51 | $13.62 \pm 0.25$ | $20.98 \pm 0.61$ | $-0.445$ | 2.6 |
| LRG | $0.6-0.8$ | 771,875 | 0.71 | $16.85 \pm 0.32$ | $20.08 \pm 0.60$ | $-0.420$ | 4.0 |
| LRG+ELG | $0.8-1.1$ | 1,876,164 | 0.93 | $21.71 \pm 0.28$ | $17.88 \pm 0.35$ | $-0.389$ | 6.5 |
| ELG | $1.1-1.6$ | 1,415,687 | 1.32 | $27.79 \pm 0.69$ | $13.82 \pm 0.42$ | $-0.444$ | 2.7 |
| QSO | $0.8-2.1$ | 856,652 | 1.49 | — | — | $26.07 \pm 0.67$ | 1.5 |
| Lya QSO | $1.77-4.16$ | 709,565 | 2.33 | $39.71 \pm 0.94$ | $8.52 \pm 0.17$ | $-0.477$ | — |

**Table 1**. Statistics for the DESI samples used for the DESI DR1 BAO measurements used in this paper. For each tracer and redshift range we quote the number of objects ($N_{\rm tracer}$), the effective redshift ($z_{\rm eff}$) and effective volume ($V_{\rm eff}$). Note that for each sample we measure either both $D_{\rm M}/r_{\rm d}$ and $D_{\rm H}/r_{\rm d}$, which are correlated with a coefficient $r$, or $D_{\rm V}/r_{\rm d}$. Redshift bins are non-overlapping, except for the shot-noise-dominated measurements that use QSO (both as tracers and for Ly$\alpha$ forest).


Johannes Lange
DESI x lensing
Minh Nguyen
Cosmology analysis
Sikandar Hanif
Fiber assignment
Uendert Andrade
Blinding validation
Tianke Zhuang
Cosmology analysis
Otávio Alves
Covariance matrix
Dragan Huterer
co-lead Cosmology analysis
Greg Tarlé
Positioners
Humna Awan
Ly-alpha
Michael Schubnell
Positioners
Monica Valluri
Milky-way science
Tim Fanning
Positioners
Sean MacBride
Focal plane, detectors
Rebekah Sebok
Focal plane
Jiaming Pan
Cosmology analysis

# COVARIANCE MATRICES

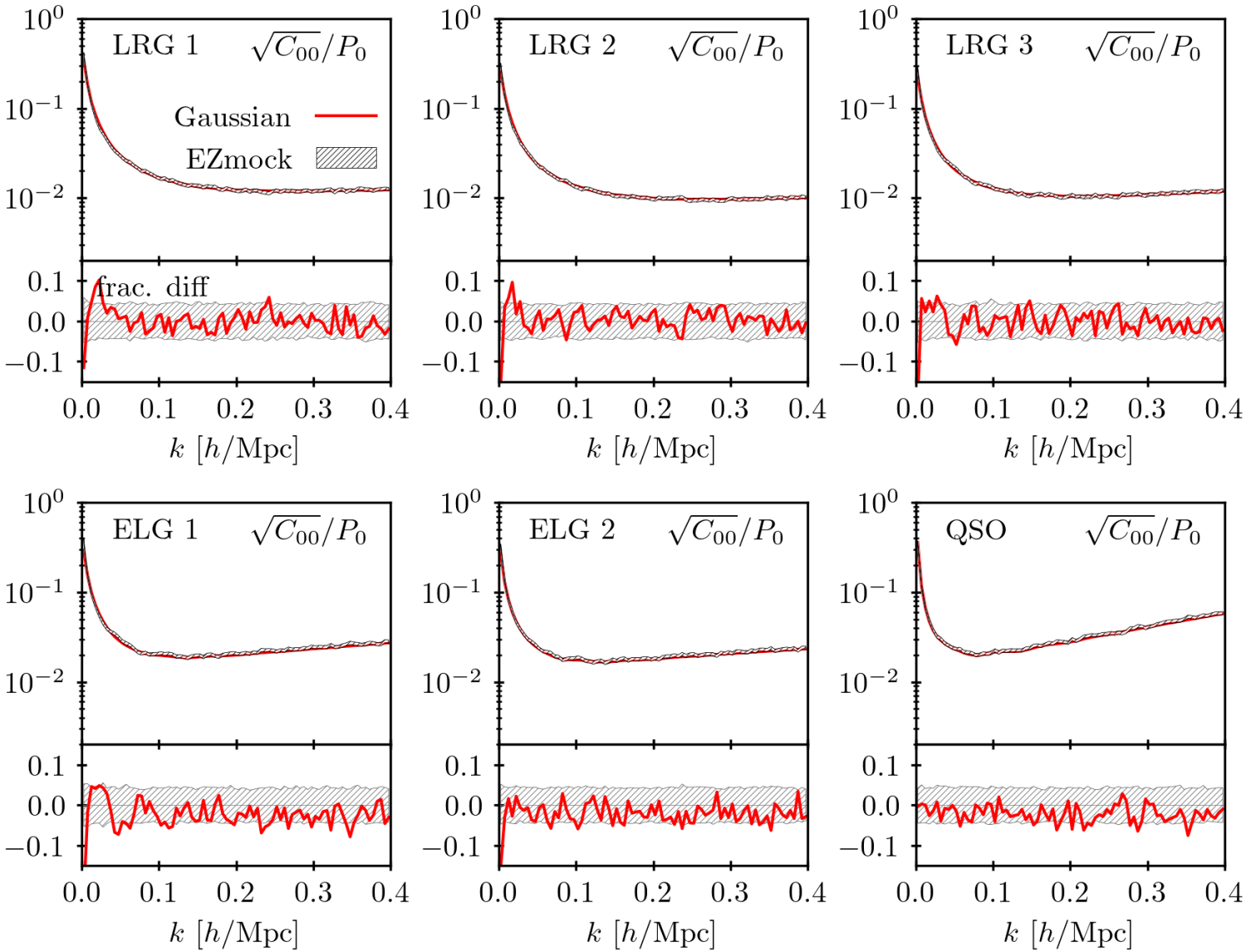



thecov

**theoretical covariances of power spectrum multipoles**

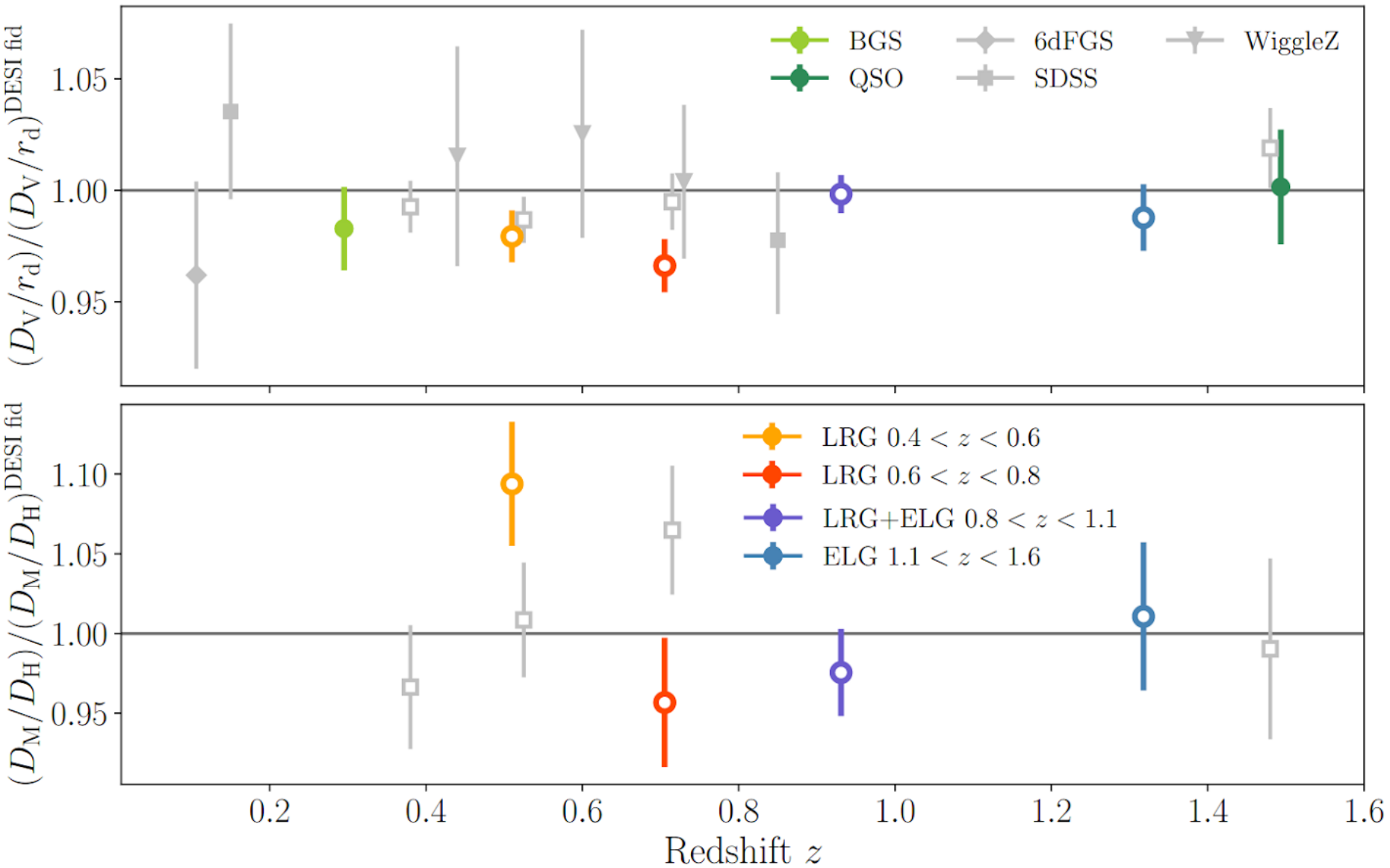
- Based on **Wadekar & Scoccimarro 2019**.
- Trispectrum at tree-level using **Kobayashi 2023**.

# VALIDATED AGAINST MOCKS

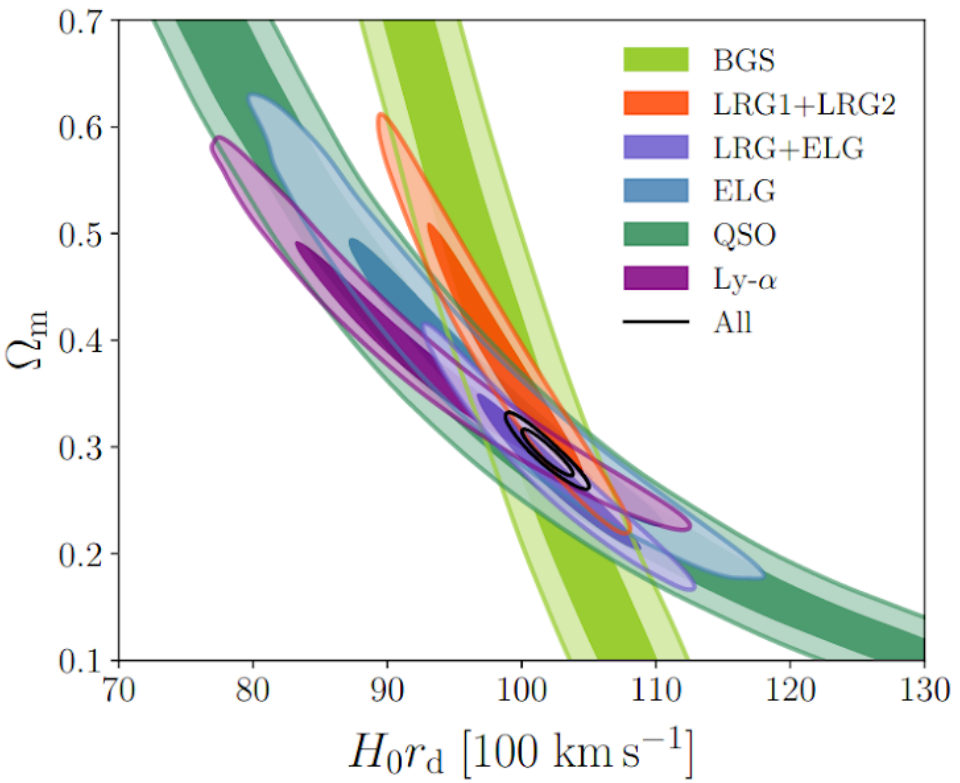


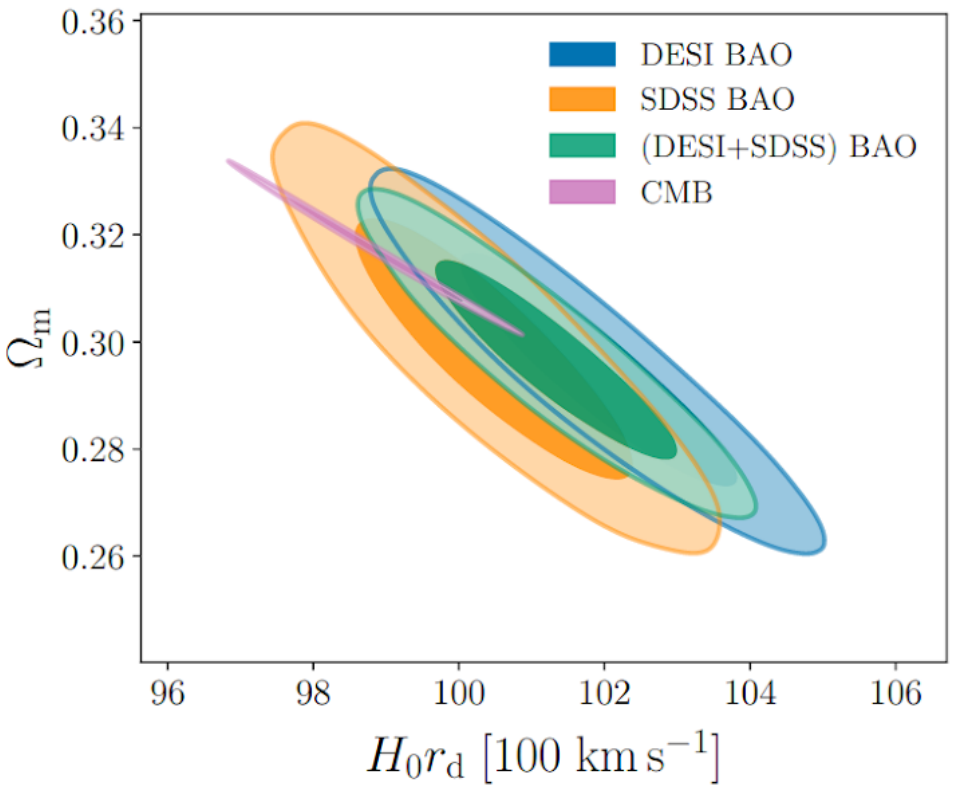
# BAO COSMOLOGY

# THE BAO MEASUREMENTS

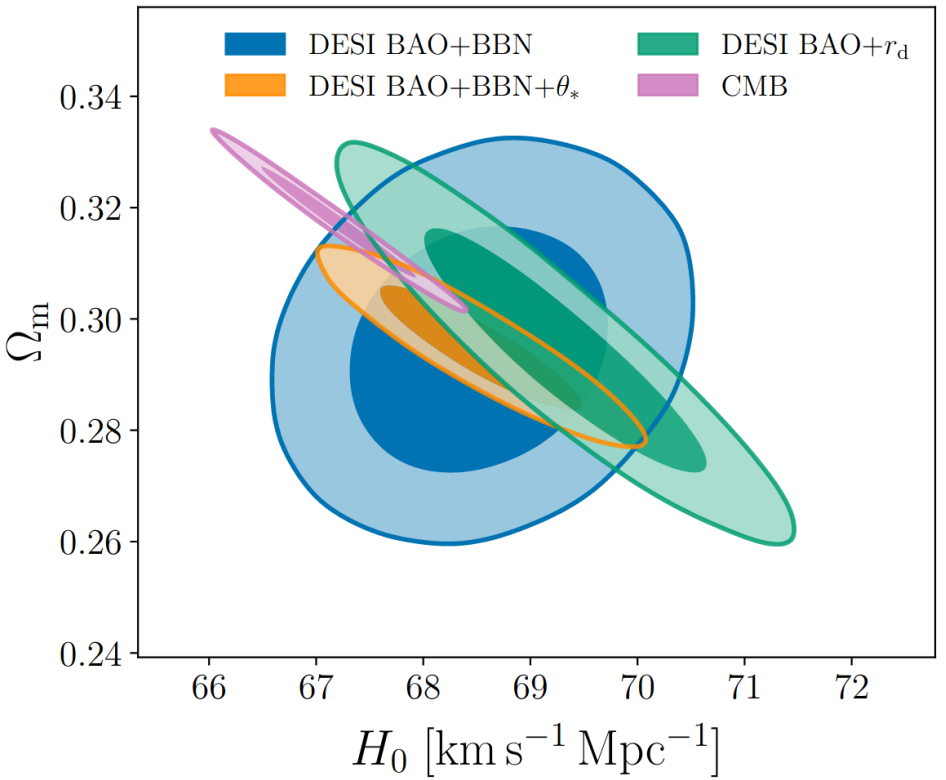


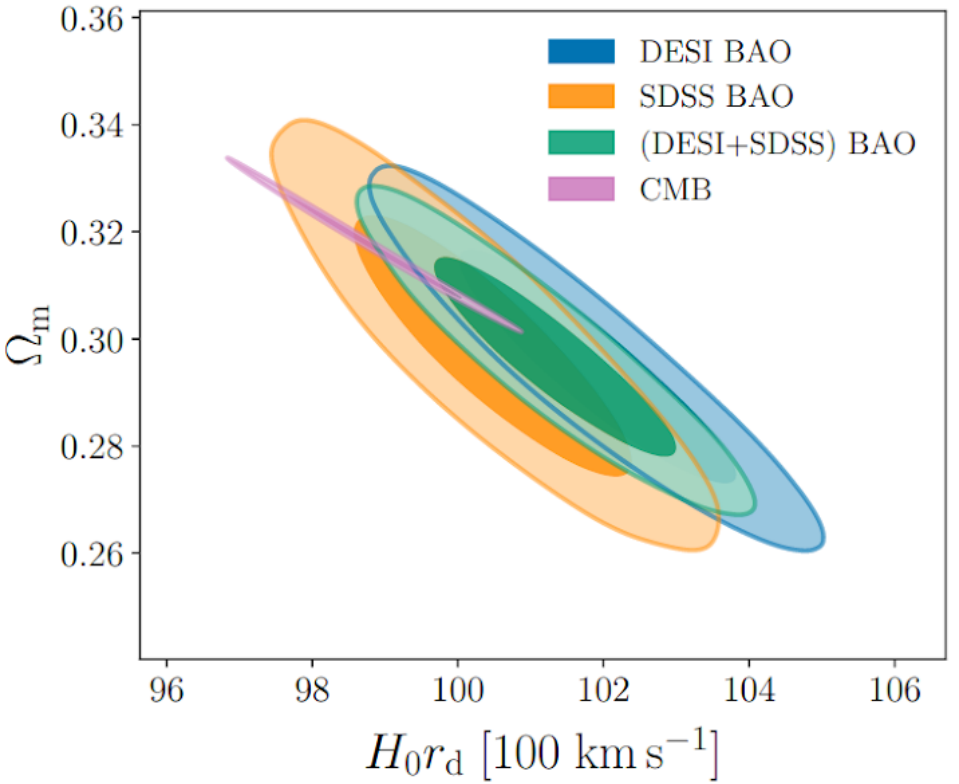
# COMBINING BAO FROM MULTIPLE REDSHIFTS



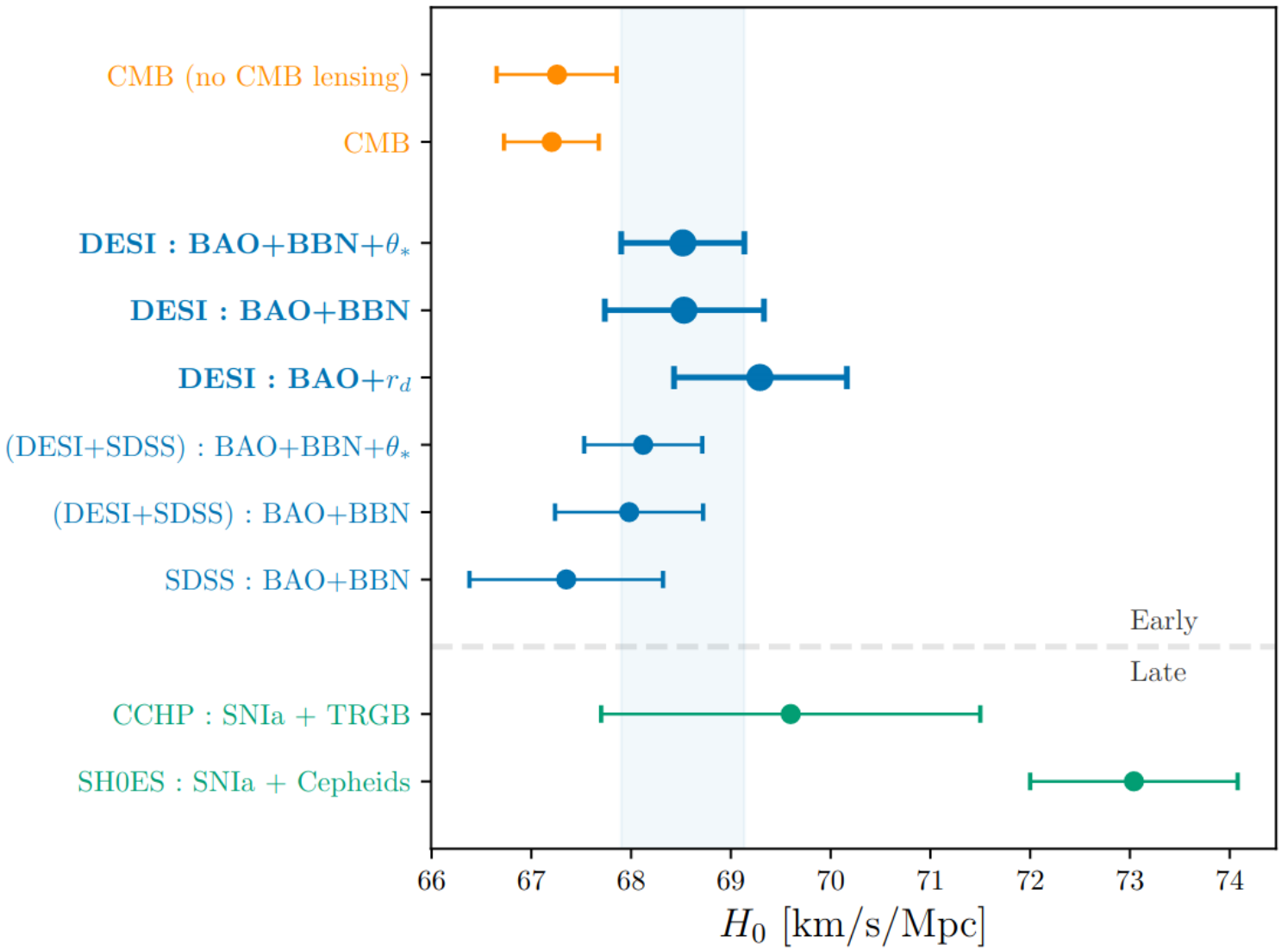



# ADDING INFO ON THE SOUND HORIZON SCALE



# YIELDS AN $H_0$ CONSTRAINT



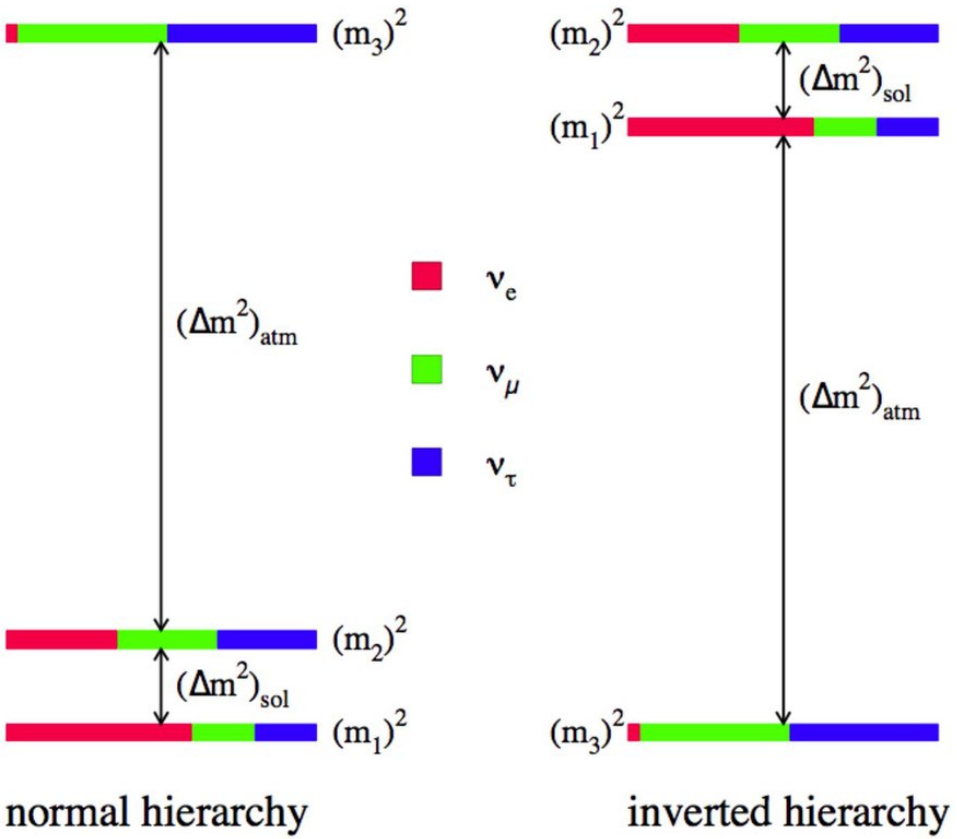
# NEUTRINOS

# NEUTRINO MASSES

Neutrino oscillations constrain squared mass **differences**.

Lowest total mass of the neutrino sector:

- Normal hierarchy: 0.059 eV
- Inverted hierarchy: 0.10 eV

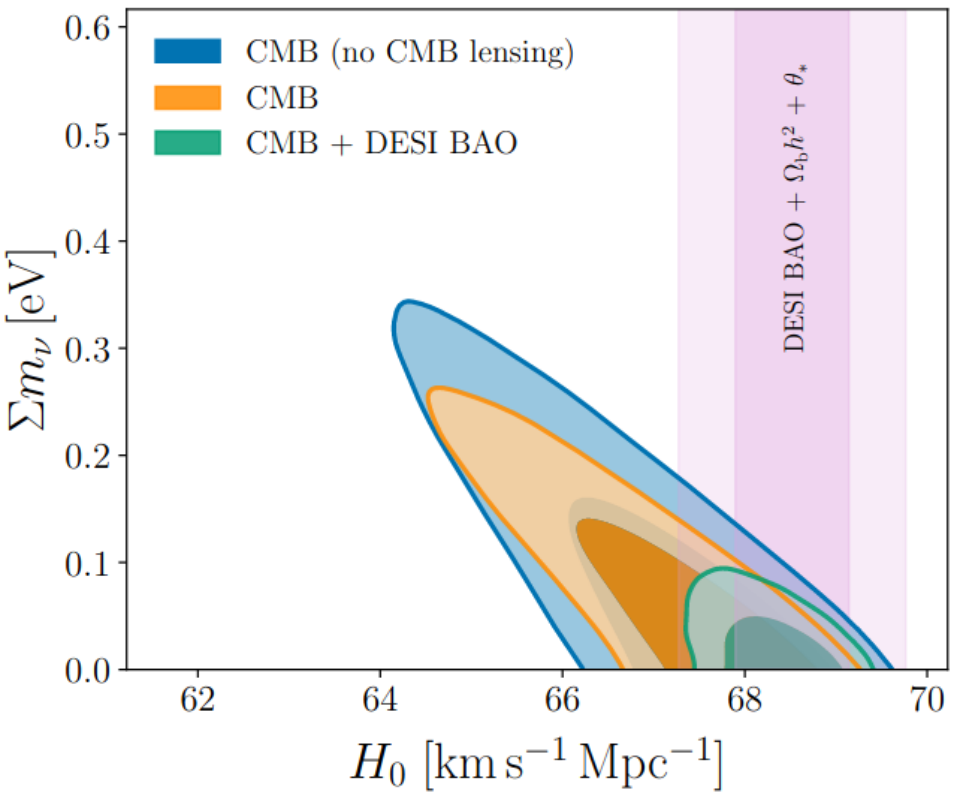


# CMB IS SENSITIVE TO THE SUM OF MASSES

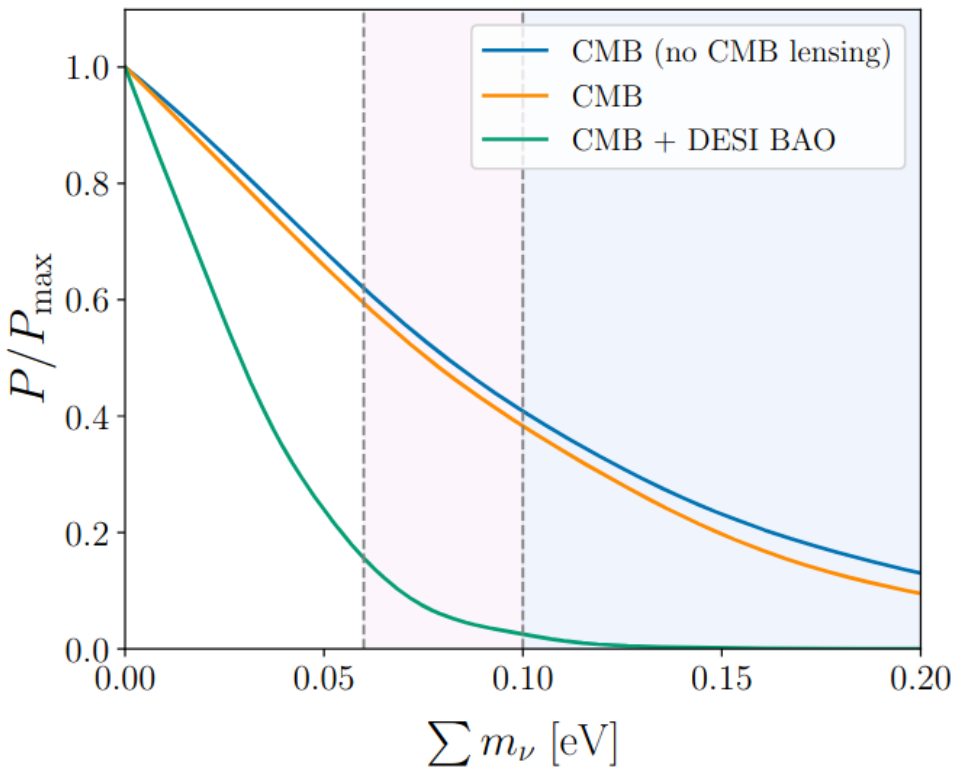
angular diameter distance to recombination

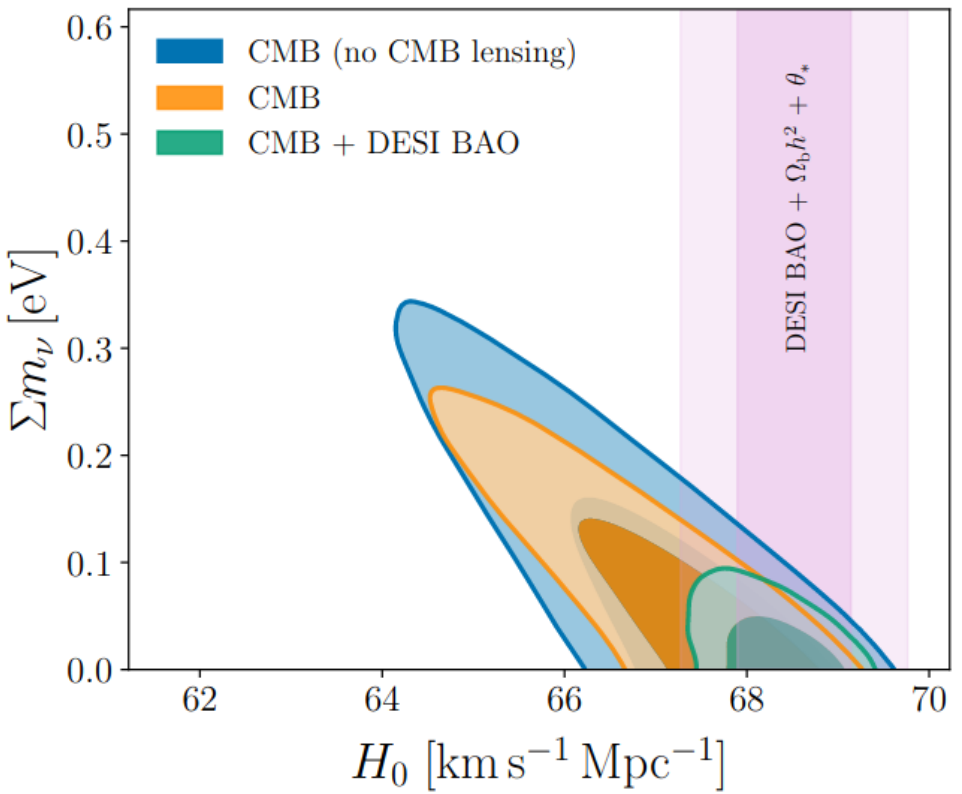
neutrino effects in CMB lensing

But thats's degenerate with the **Hubble constant** and **matter density**.

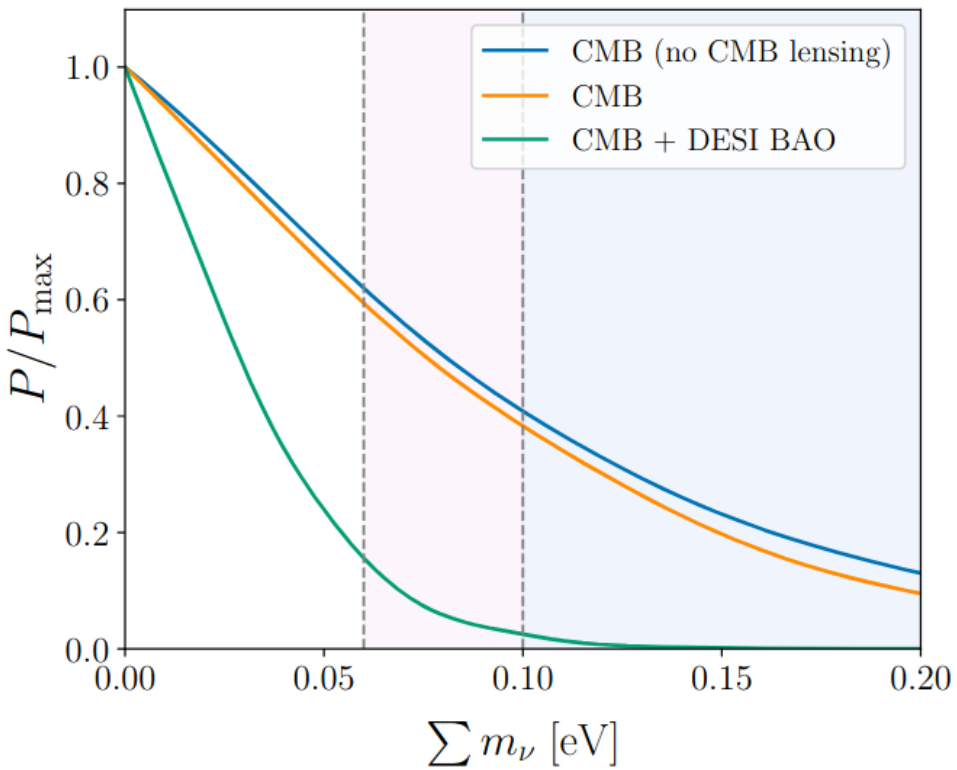


# COMBINING WITH DESI BAO



# COMBINING WITH DESI BAO



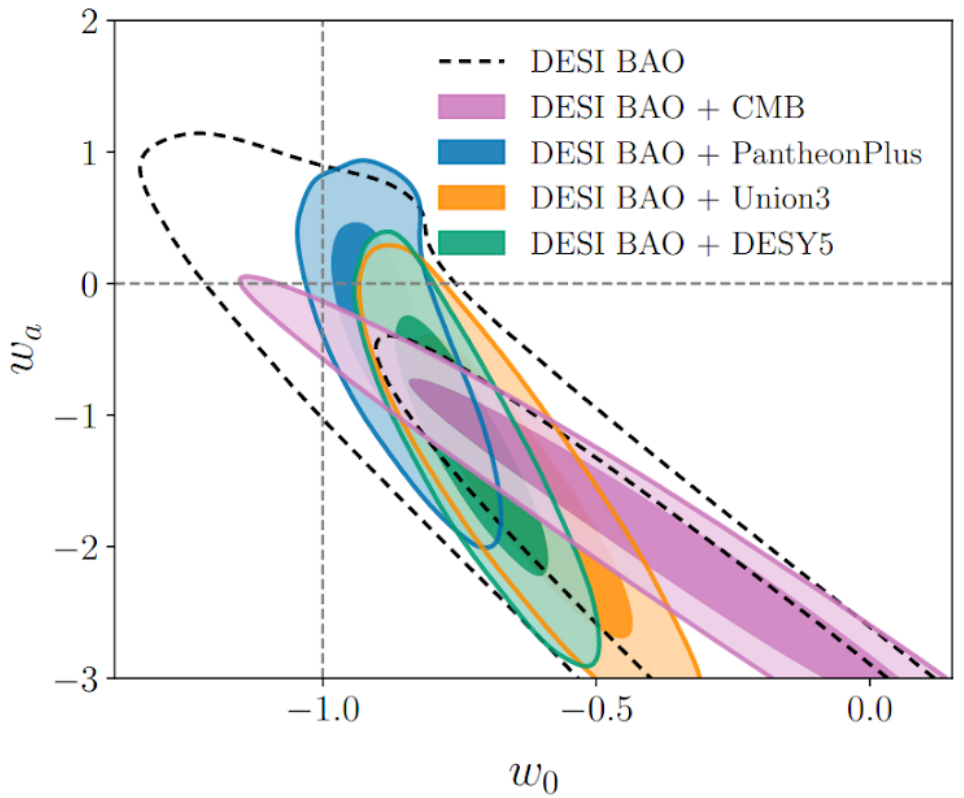

$$\sum m_\nu < 0.072\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ BAO{+}CMB}),$$

$$\sum m_\nu < 0.113\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ BAO{+}CMB};\ \sum m_\nu > 0.059\,\mathrm{eV}),$$

$$\sum m_\nu < 0.145\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ BAO{+}CMB};\ \sum m_\nu > 0.10\ \mathrm{eV}).$$

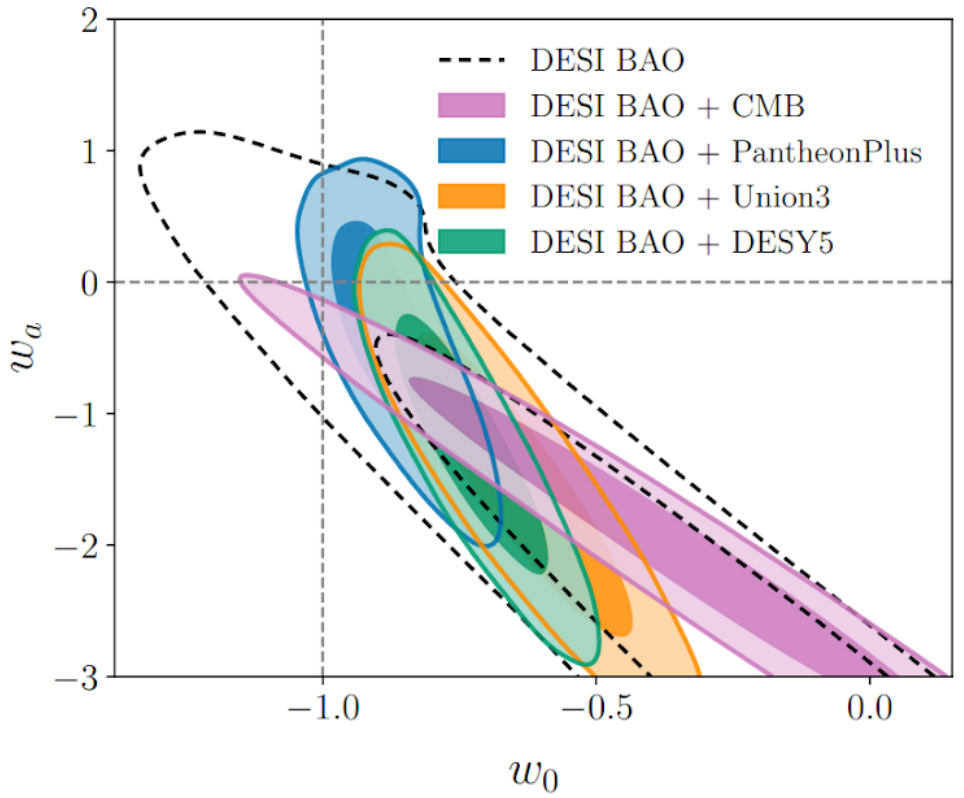
# DARK ENERGY

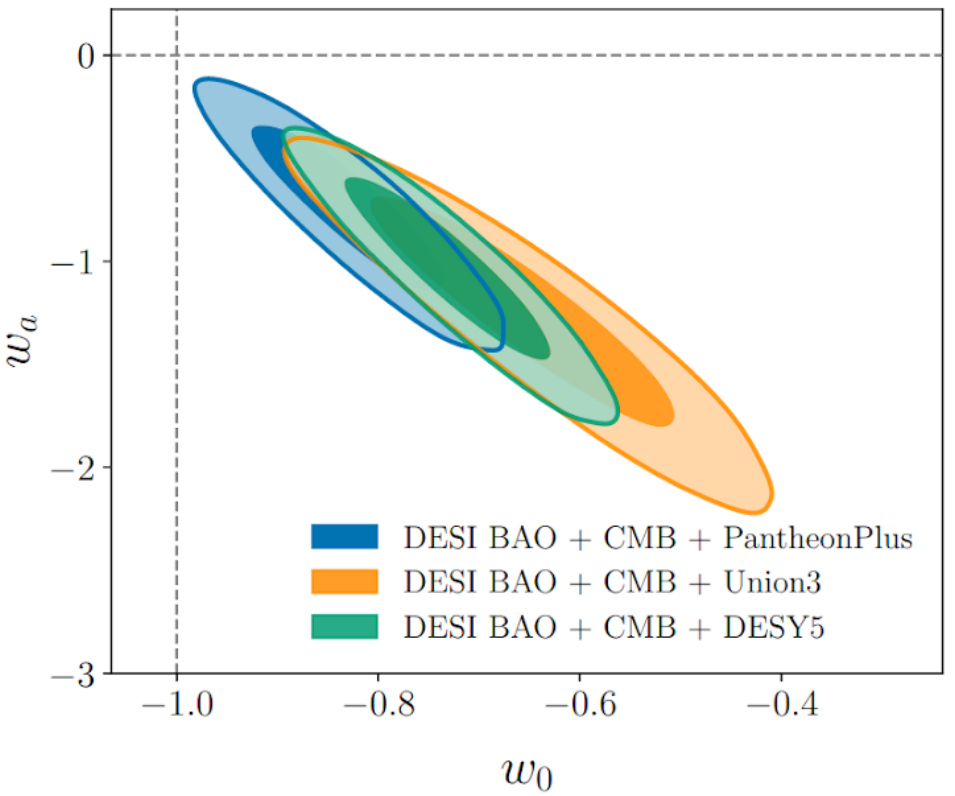
# NO DYNAMICAL DE IN DESI, CMB OR SN ALONE




$$w(a) = w_0 + w_a(1 - a)$$

# DESI+SN+CMB POINTS AT TIME-EVOLVING $w(a)$



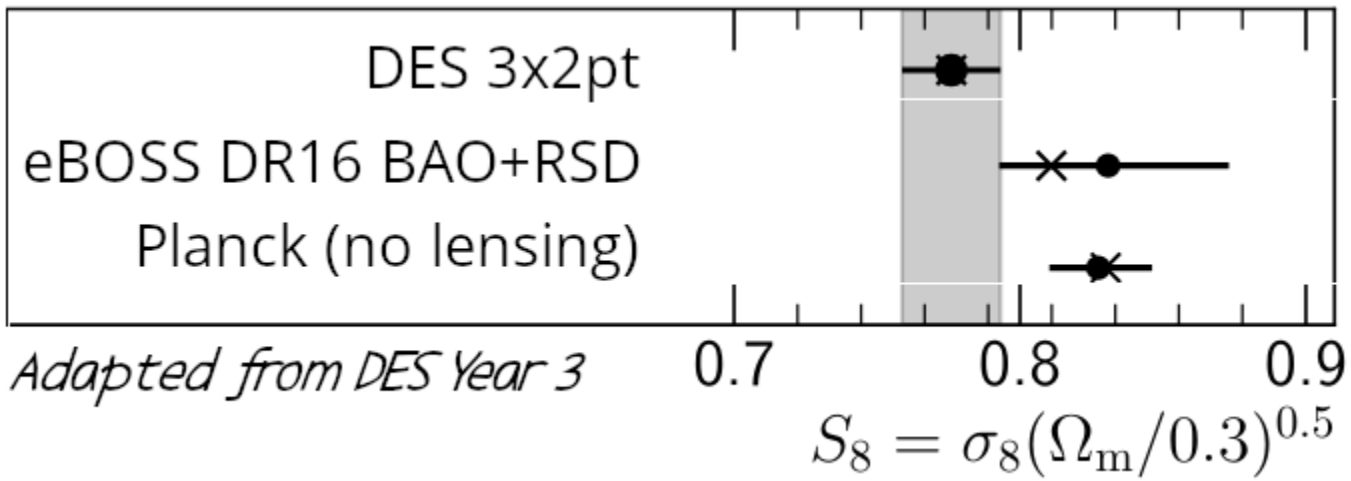
# DESI 2024 PAPERS

- DESI 2024 I: First year data release
- DESI 2024 II: DR1 catalogs
- ✅ **DESI 2024 III: BAO from Galaxies and Quasars at z < 2**
- ✅ **DESI 2024 IV: BAO from the Lyman-α Forest at z > 2**
- DESI 2024 V: RSD from Galaxies and Quasars at z < 2
- ✅ **DESI 2024 VI: Cosmological constraints from BAO measurements**
- DESI 2024 VII: Cosmological constraints from RSD measurements
- + many supporting papers.

P.S.: Next BAO release is right around the corner.

# EXPECTATIONS FOR FULL-SHAPE MEASUREMENTS

**$S_8$ tension**



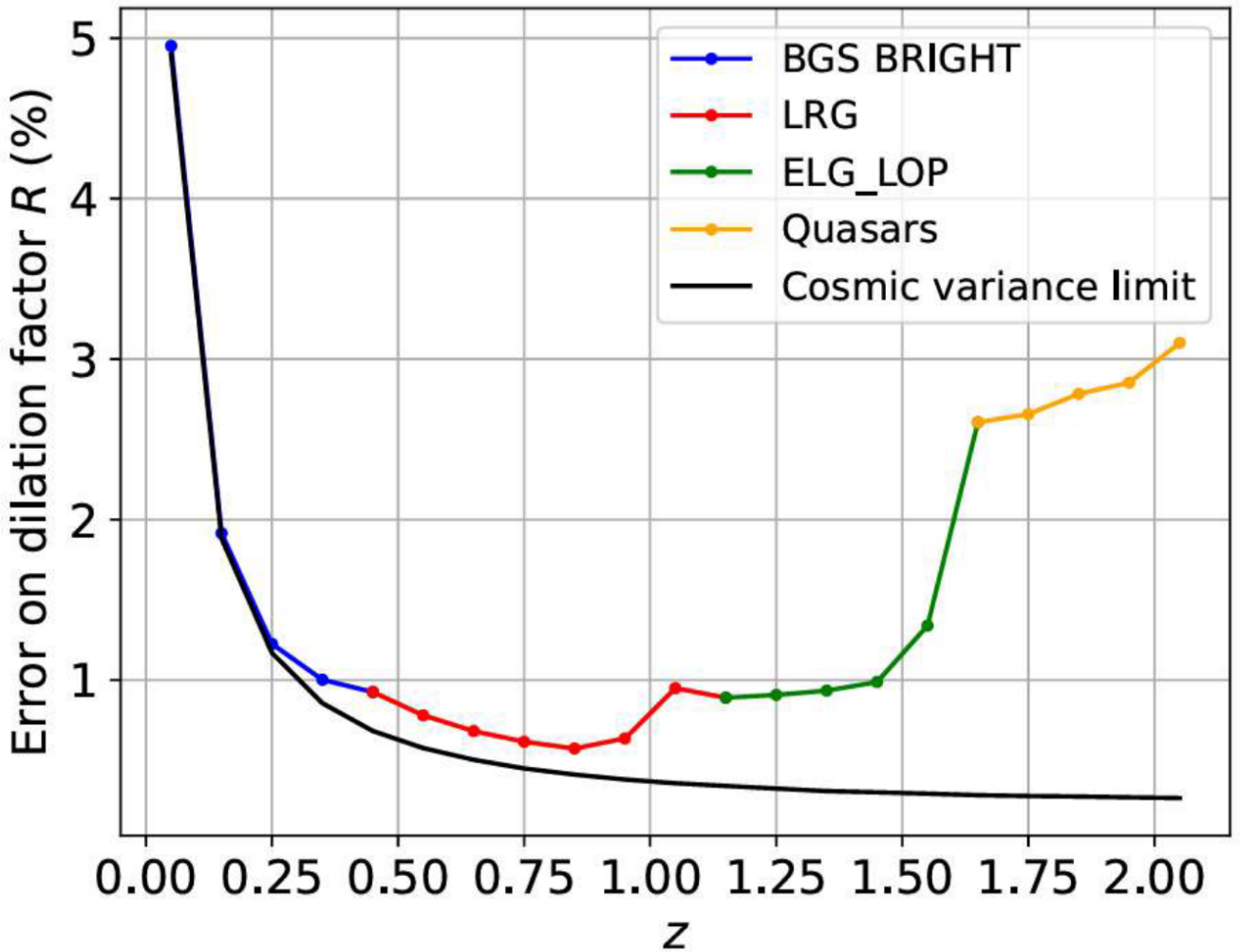

**Neutrino masses:** addition of broadband information,

**Dark energy:** impact on growth of structure,

+ other models **beyond ΛCDM**.

# FUTURE

# THERE'S MARGIN FOR FURTHER IMPROVEMENT




**BGS**
cosmic variance limited

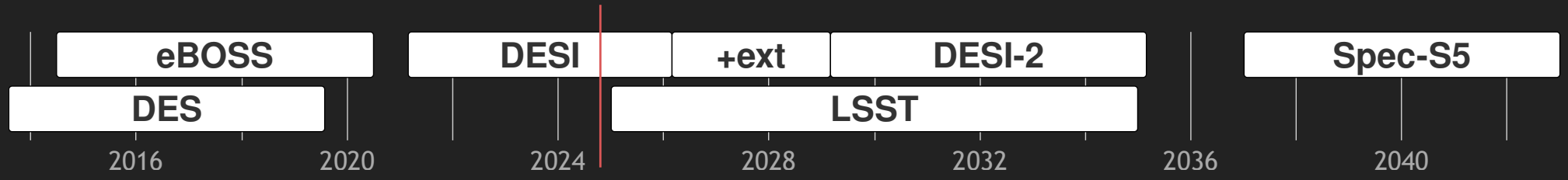
**LRG**
new targets and easy redshifts

**ELG**
more targets than fibers

**QSO**
hard to identify new targets

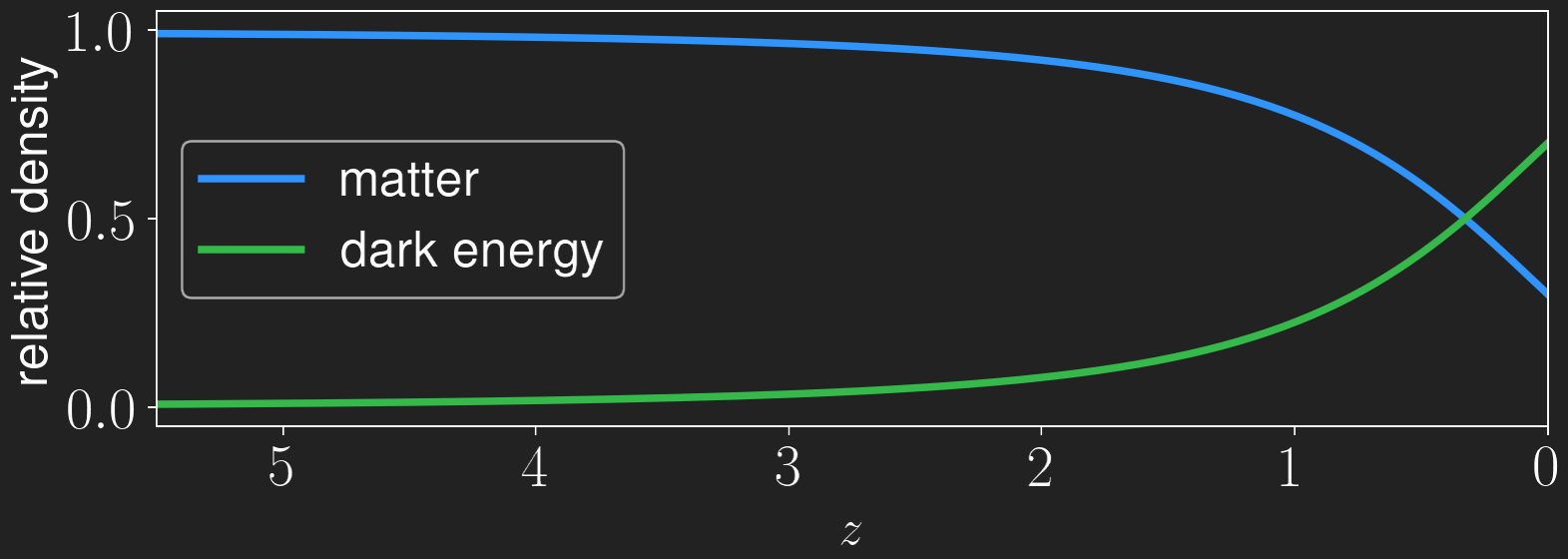
# DESI EXTENSION

- Same instrument
- +20% area
- +50% overlap with LSST
- +50% LRG targets



# DESI-2

- Focus at higher redshifts: $2.2 < z < 5$
  - More linear modes for primordial physics studies
  - Dark Energy in the matter-dominated era




- Instrument upgrades: Skipper CCDs for blue
- New tracers: Lyman-break galaxies (LBG) & Lyman-α emitters (LAE)

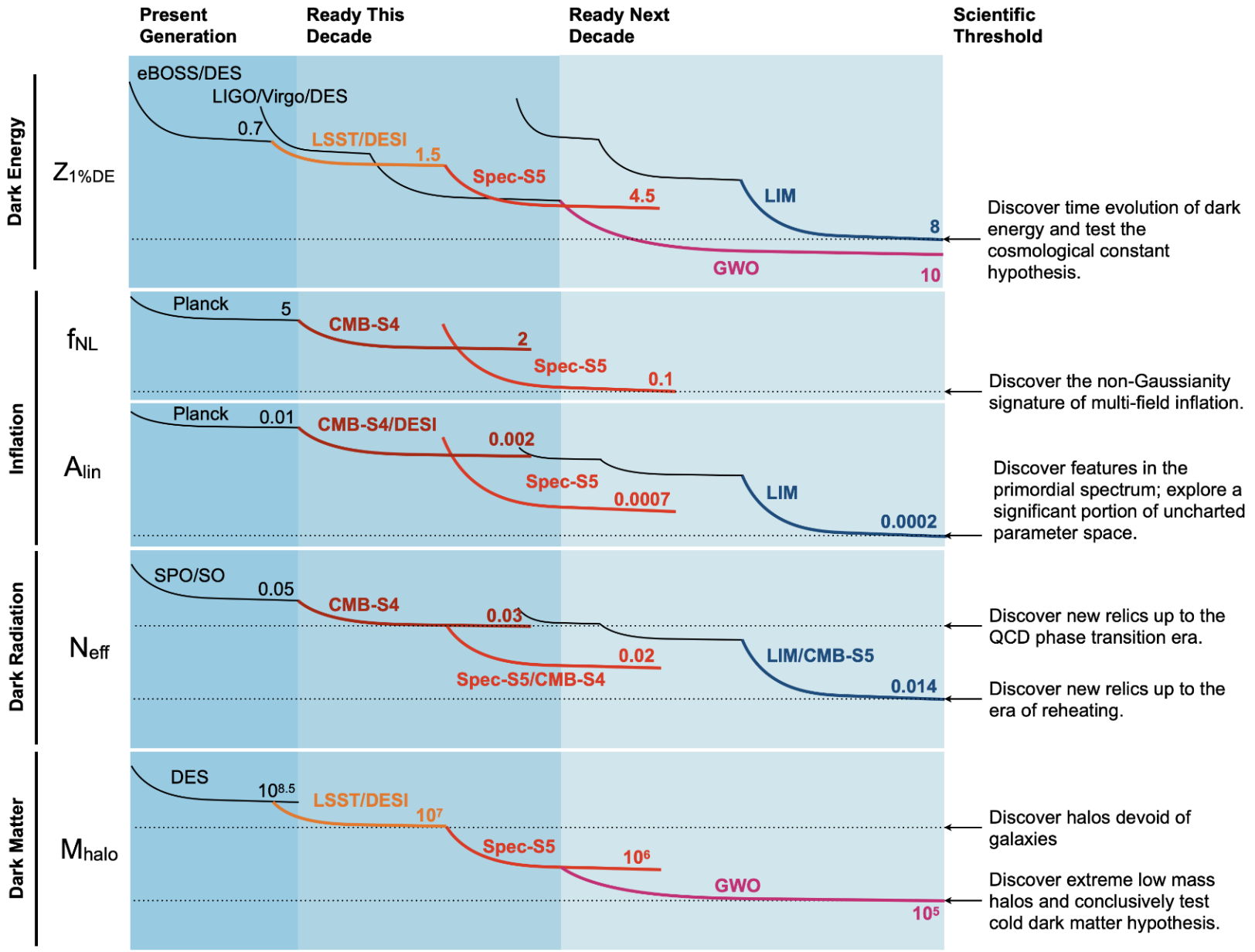
# EARLY RESULTS FROM BOTH **DESI** AND LSST WILL **SHAPE** FUTURE PRIORITIES

Together with a potential **DESI upgrade**, they will inform the design of a **next-generation spectroscopic survey** by telling us **which** potential **science goals** should be emphasized.

**P5 2023 report**

# SPEC-S5

- 2 telescopes: Mayall + Blanco
- Mirror upgrade: from 4m to 6m
- Instrument upgrade: 3 fibers per positioner = 26k fibers per telescope
- Science cases:
  - High redshift program
  - High number density at $z < 2$
  - Milky Way science (50M stellar spectra), stellar streams, dark matter


Present Generation
Ready This Decade
Ready Next Decade
Scientific Threshold
Dark Energy
$z_{1\%DE}$
eBOSS/DES
LIGO/Virgo/DES
0.7
LSST/DESI
1.5
Spec-S5
4.5
LIM
8
GWO
10
Discover time evolution of dark energy and test the cosmological constant hypothesis.
Inflation
$f_{NL}$
Planck
5
CMB-S4
2
Spec-S5
0.1
Discover the non-Gaussianity signature of multi-field inflation.
$A_{lin}$
Planck
0.01
CMB-S4/DESI
0.002
Spec-S5
0.0007
LIM
0.0002
Discover features in the primordial spectrum; explore a significant portion of uncharted parameter space.
Dark Radiation
$N_{eff}$
SPO/SO
0.05
CMB-S4
0.03
0.02
Spec-S5/CMB-S4
LIM/CMB-S5
0.014
Discover new relics up to the QCD phase transition era.
Discover new relics up to the era of reheating.
Dark Matter
$M_{halo}$
DES
$10^{8.5}$
LSST/DESI
$10^{7}$
Spec-S5
$10^{6}$
GWO
$10^{5}$
Discover halos devoid of galaxies
Discover extreme low mass halos and conclusively test cold dark matter hypothesis.

# SUMMARY

- Galaxy spectroscopic surveys entered a new era with DESI
- DR1 BAO measurements have interesting implications for:
  - Neutrinos, Dark Energy
- Full-shape measurements coming up soon
- Next BAO release not long after that
- Spectroscopic surveys = good data for a few decades
- DESI-2 will explore higher redshifts
- Spec-S5 will push constraints in primordial physics